First steps of numerical simulation using Artificial Intelligence

Vincent Vadez, François Brunetti, Pierre Alliez

First Steps of Numerical Simulation using Artificial Intelligence

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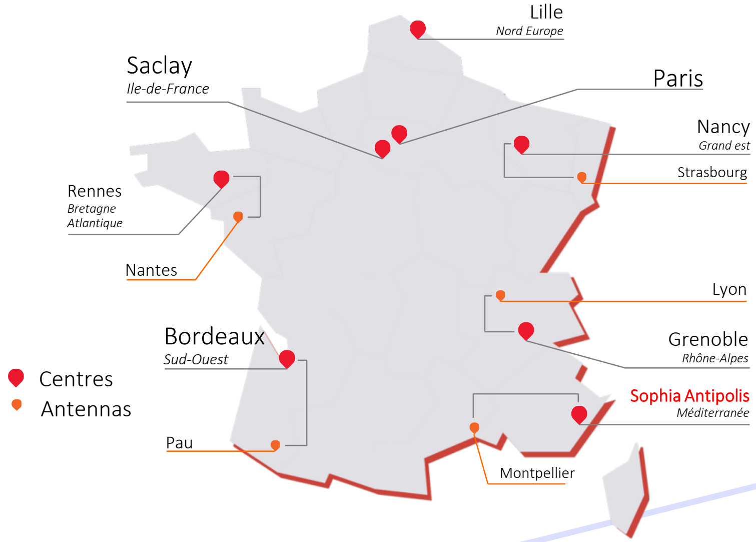
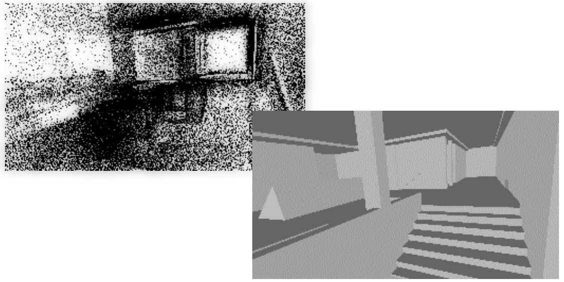
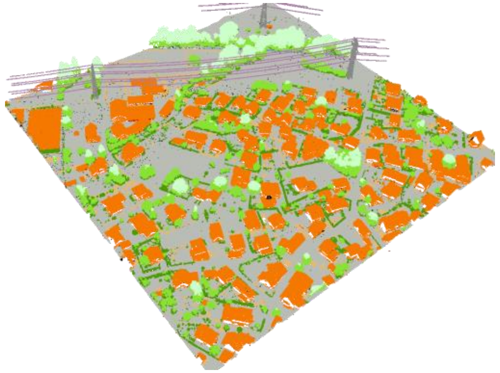
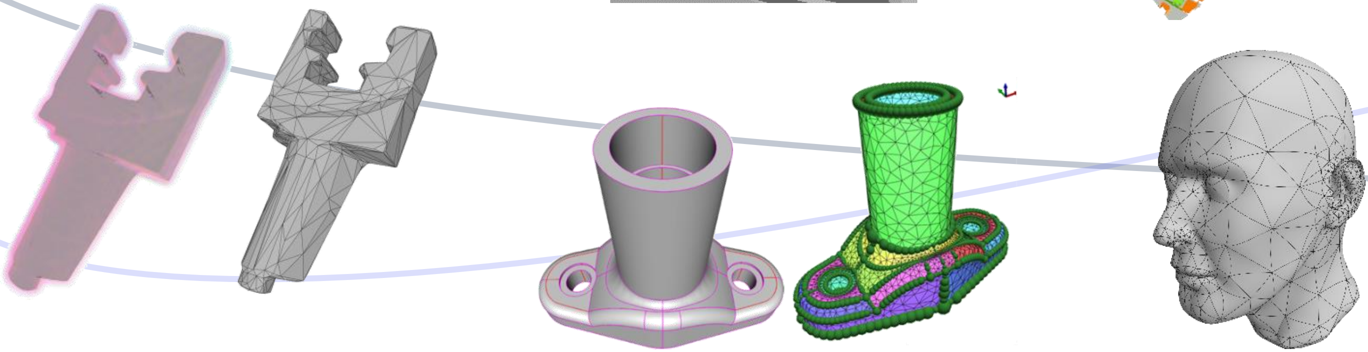
Project-Team *Titane*

- **Geometric modeling of 3D scenes from measurement data**
  - Analysis, reconstruction, approximation
  - Computational geometry, geometry processing, machine learning









CONTEXT AND MOTIVATIONS

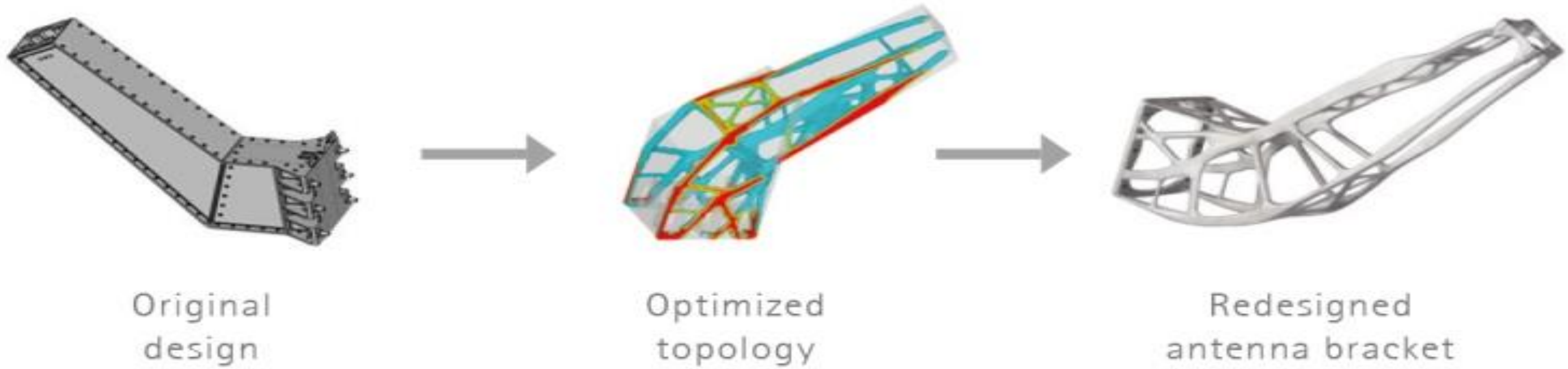


Image from www.eos.info

- **Additive manufacturing yields increasingly complex objects**
  - Reduced weight via topology optimization
  - Many more facets elements are required to describe these free-form shapes, which are later added to the full satellite model.

CONTEXT AND MOTIVATIONS

- **Context of real-time simulation & sensibility**
  - Radiative thermal simulation is time-consuming: $O(\boldsymbol{n}^2)$ complexity for the view factors, with ***n*** the number of faces of the mesh.
  - Full simulation intractable on the complete satellite model, in a reasonable time.
  - A thermal-aware geometric approximation process is required, allowing real-time simulation and beyond (multi-physics simulation and predictions).

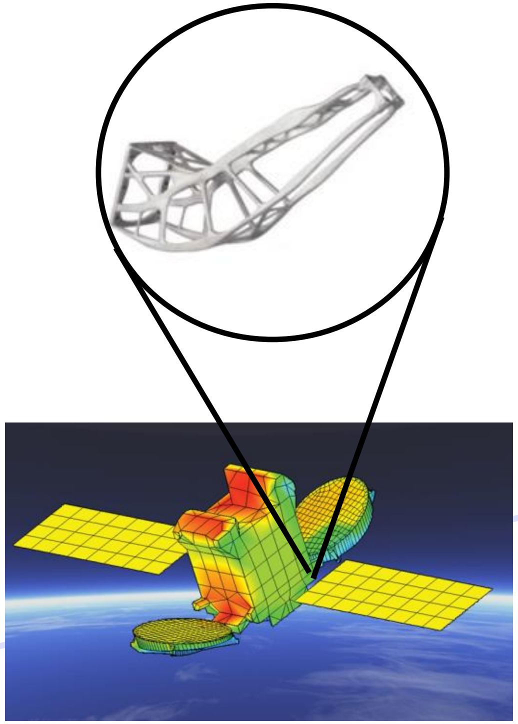
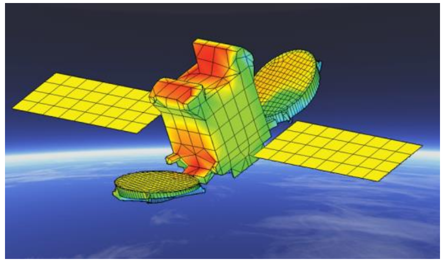


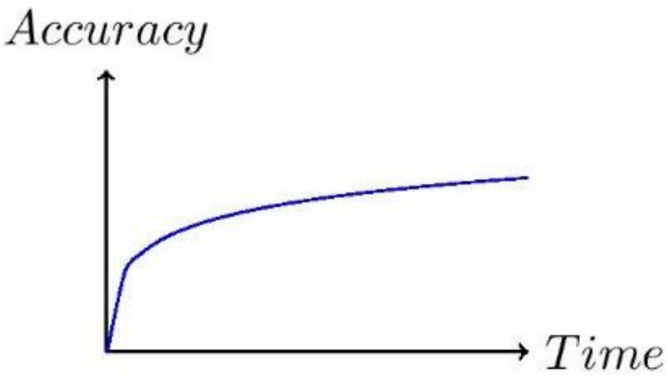
Image from www.ata-e.com

PROBLEM STATEMENT

- **Input**: Complex surface mesh (many facets and occlusions, created by a CAD software)



- **Output:** Approximated model respecting the view factors of the thermal nodes



- **Guarantees:** Error bounds under wide range of configurations and conditions
- **Goal**: Optimize trade-off between accuracy and time

DIRECTIONS

- **Topic of Ph.D. thesis:** Design a geometric approximation method preserving a *simulation-aware* error metric rather than a *geometric* error metric.
- **Application to space thermal analysis:** view factor computation and model reduction
- **Goals:**
  - Compute reference view factors
  - Compare with approximated view factors
  - Evaluate simulation with approximation
  - Utilize supervised machine learning to automate the reduction process, leveraging a large training dataset.

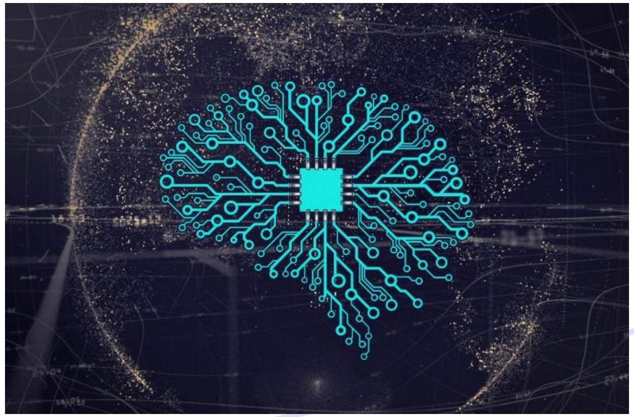
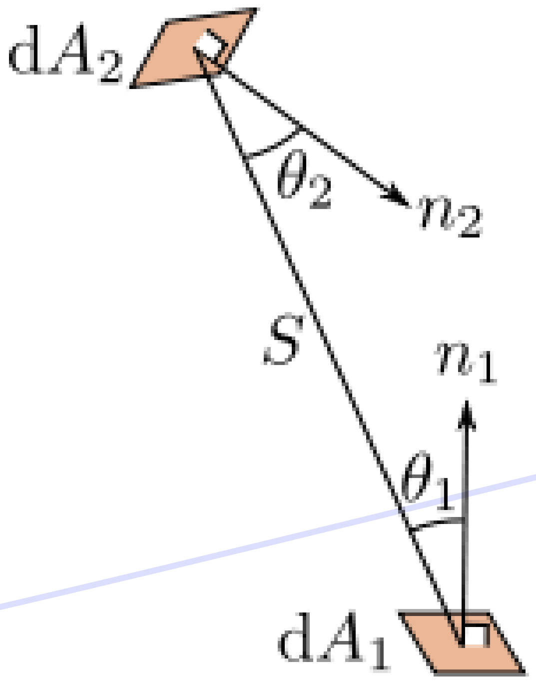


Image from www.warontherocks.com

VIEW FACTOR

$$F_{1\to 2} = \frac{1}{A_1}\int_{A_1}\int_{A_2}\frac{\cos\theta_1\cos\theta_2}{\pi s^2}\,\mathrm{d}A_2\,\mathrm{d}A_1$$

$$dF_{1\to 2} = \frac{\cos\theta_1\cos\theta_2}{\pi s^2}\mathrm{d}A_2$$



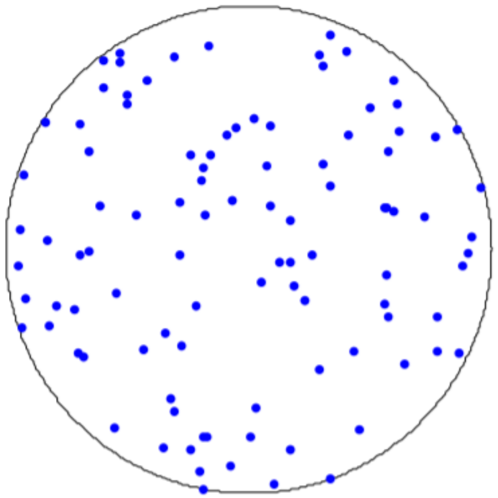
View factors depend on 3 components:

- area of the faces
- distance between them
- orientation

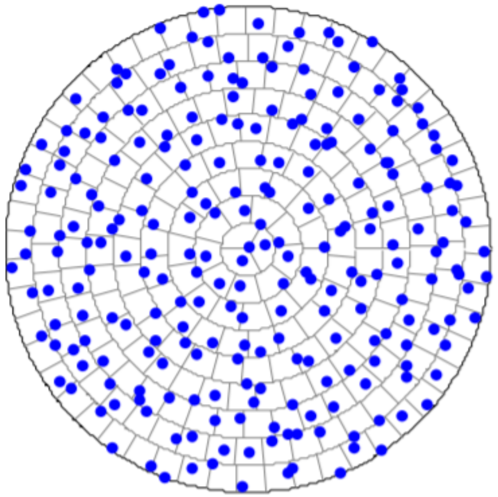
RELATED WORK

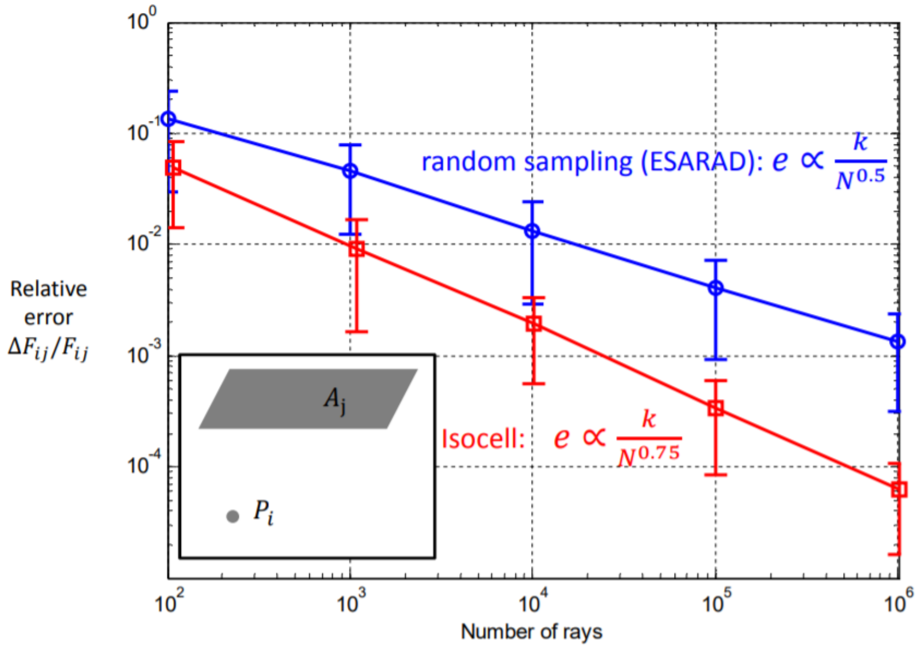
- **Accelerating computation of view factors**
  - **Jacques, Masset, Kerschen**: *Ray tracing enhancement for space thermal analysis: isocell method* , 27th Space Thermal Analysis Workshop, ESTEC.

Random (classic) sampling



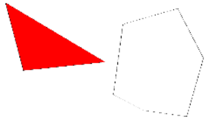
Isocell sampling





RELATED WORK

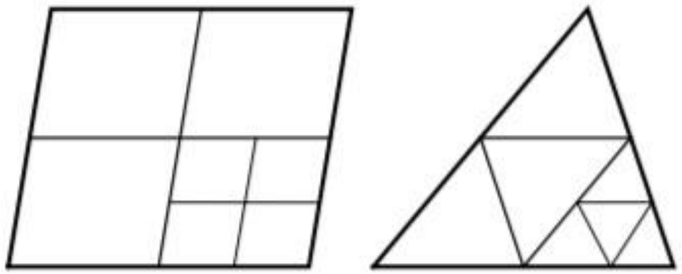
- **Schröder, Hanrahan**: *On the Form Factor between Two Polygons.* Proceedings of ACM SIGGRAPH 1993.
  → Closed form solution for the view factor between two convex polygons



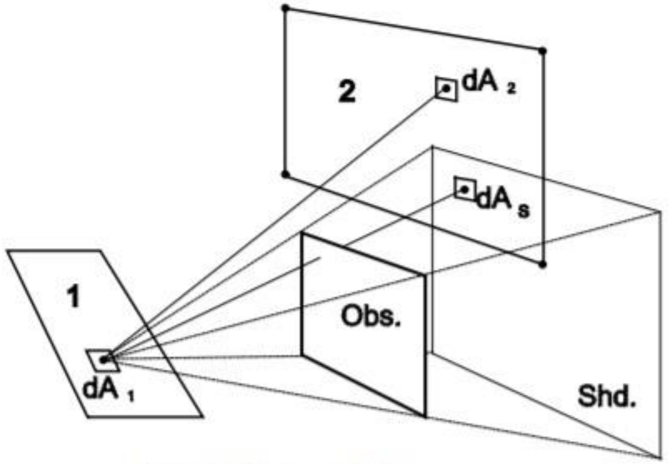
$$
\begin{aligned}
L(b)(y) &:= \int^{y} t^2(1-t^2)^{-3}\ln(b+t)\,dt = \frac{1}{16}\Bigg[\frac{-b\ln(y-1)}{(b+1)^2} - \frac{b\ln(1+y)}{(b-1)^2} + \left(\frac{2(b+y)(1+by)[(b-y)^2+(by-1)^2]}{(b^2-1)^2(y^2-1)^2} + \ln\frac{(1-y)(1-b)}{(1+y)(1+b)}\right)\ln(b+y) \\
&\qquad + \frac{2(b-y)}{(b^2-1)(y^2-1)} + \mathrm{Li}_2\left(\frac{1-y}{1+b}\right) - \mathrm{Li}_2\left(\frac{1+y}{1-b}\right)\Bigg] \\
M(y) &:= \int^{y} t^2(1-t^2)^{-3}\,dt = \frac{1}{16}\left[4y(y^2-1)^{-2} + 2y(y^2-1)^{-1} + \ln\frac{y-1}{y+1}\right] \\
G(q)(y) &:= \int^{y} \ln q(t)\,dt = \frac{q'(y)}{2a}\ln q(y) - 2y + \frac{d}{a}\tan^{-1}\frac{q'(y)}{d} \\
H(q)(y) &:= \int^{y} t\ln q(t)\,dt = \left(\frac{y^2}{2} + \frac{c}{2a} - \frac{b^2}{4a^2}\right)\ln q(y) - \frac{y(ay-b)}{2a} - \frac{bd}{2a^2}\tan^{-1}\frac{q'(y)}{d}
\end{aligned}
$$

Closed form
(without obstruction)

- **Walton**: *Calculation of Obstructed View Factors by Adaptive Integration.* NIST Report, 2002.



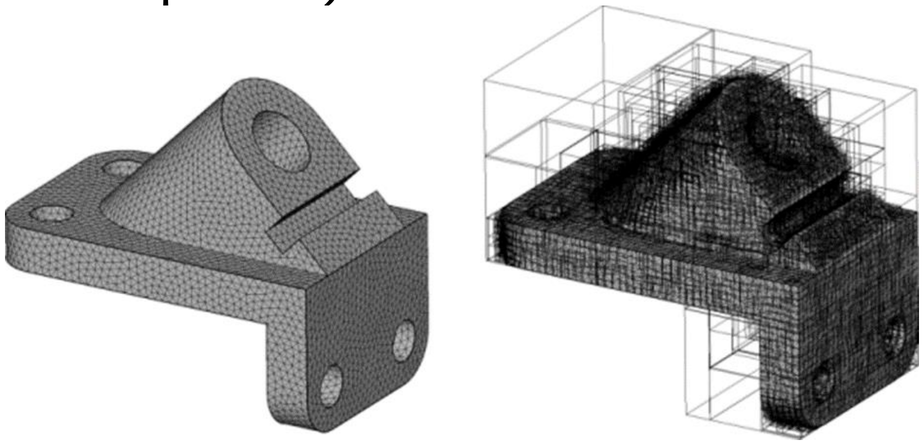
Adaptive Division of Polygons

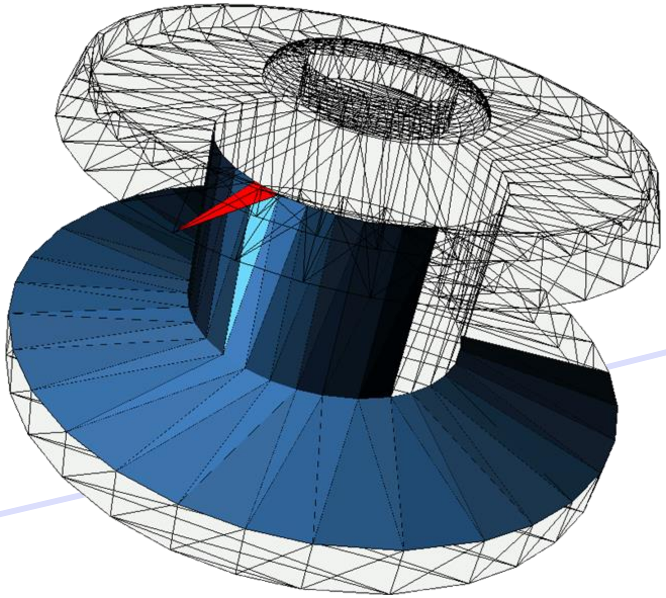


Partially Obstructed View

ACHIEVEMENTS

- **Hierarchical geometric data structure:** AABB-tree (fast intersection queries)



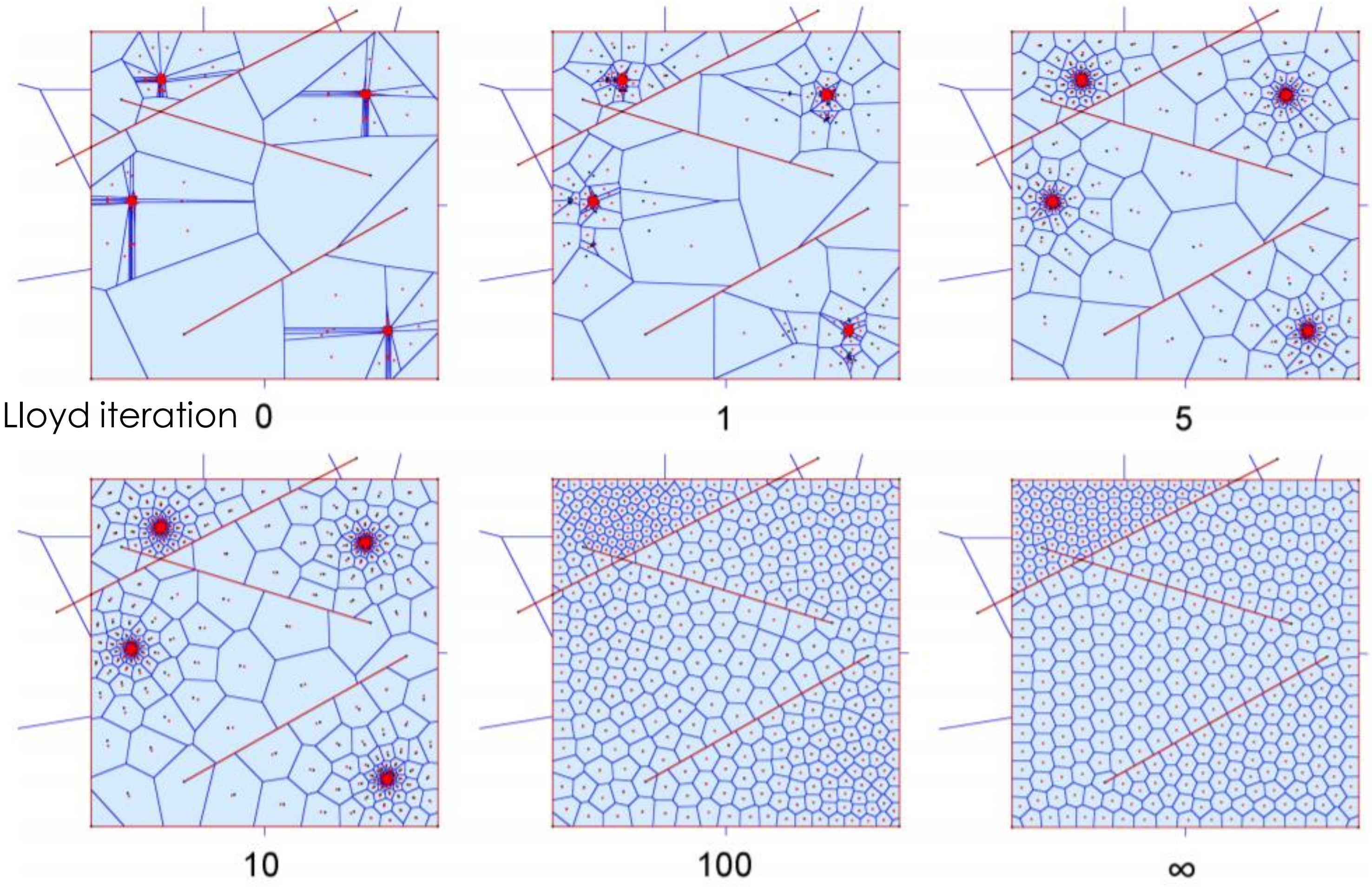


- **Closed form solution** when full visibility (**Schröder**)
- **Quadrature in the presence of occlusions:**
  - Point-based (via bounded centroidal Voronoi diagrams)
  - Triangle-based (recursive longest bisection)

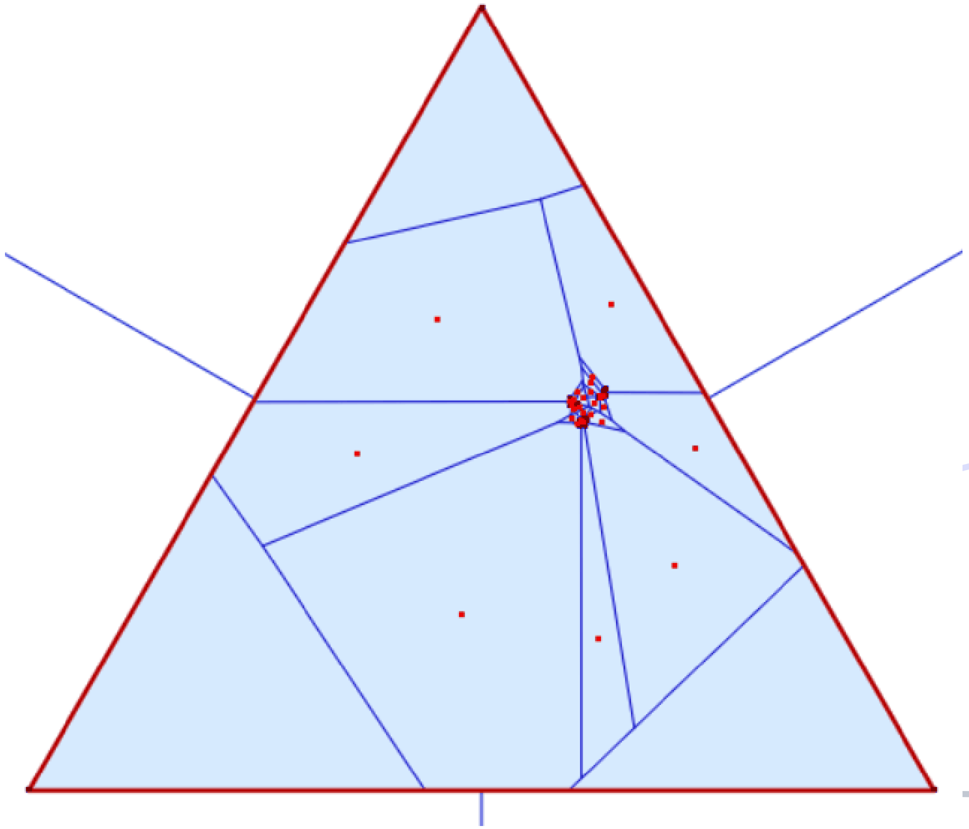
Reference view factors

Bounded Centroidal Voronoi Diagrams (CVD)

DOREA

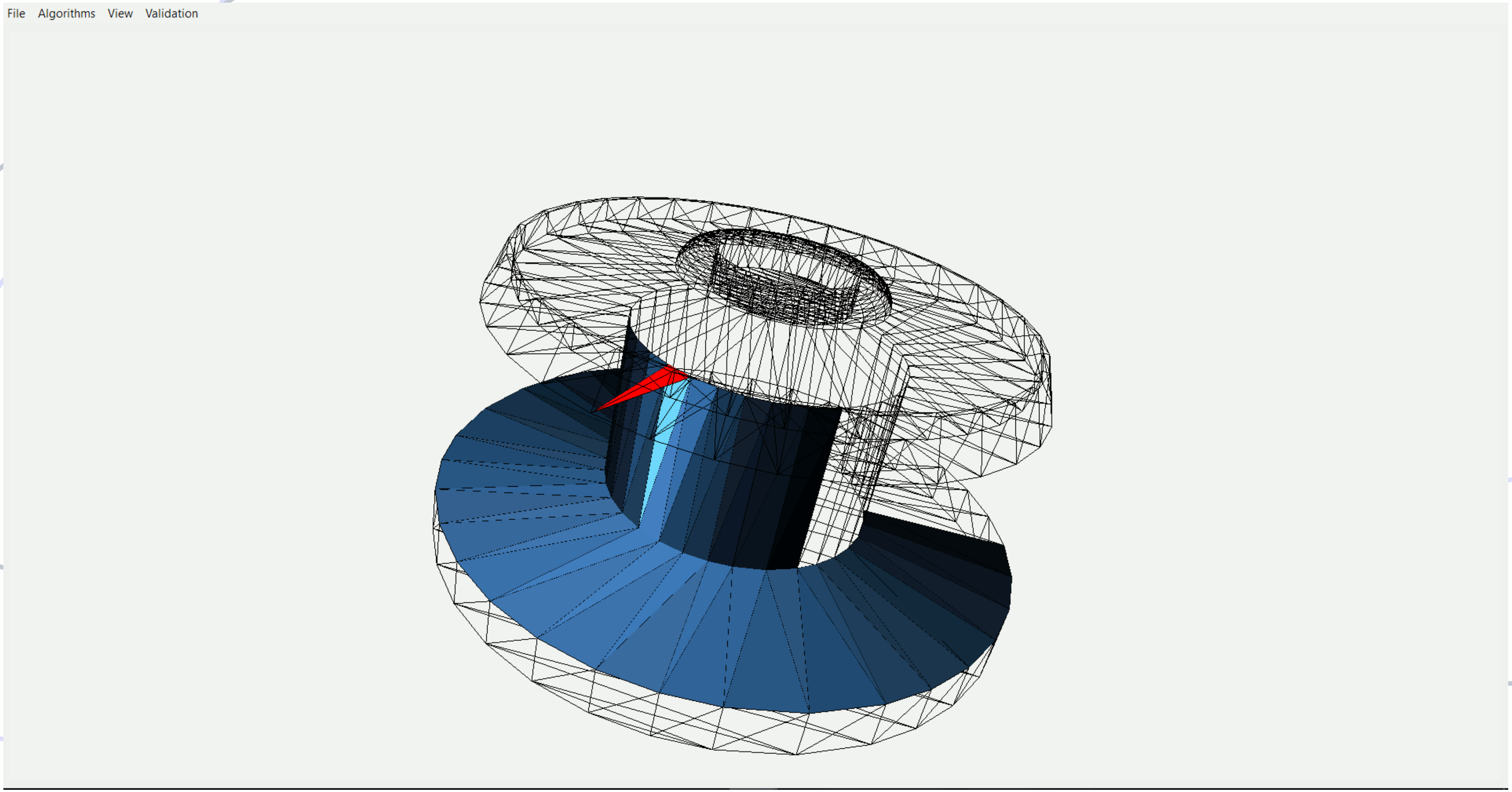


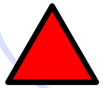
Tournois, Alliez, Devillers: *2D Centroidal Voronoi Tessellations with Constraints.*



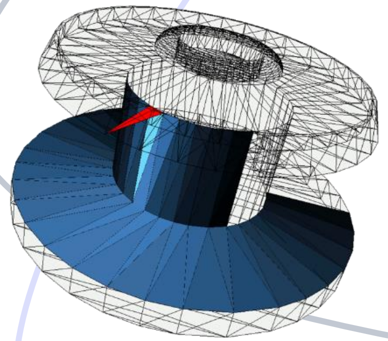
Lloyd iterations

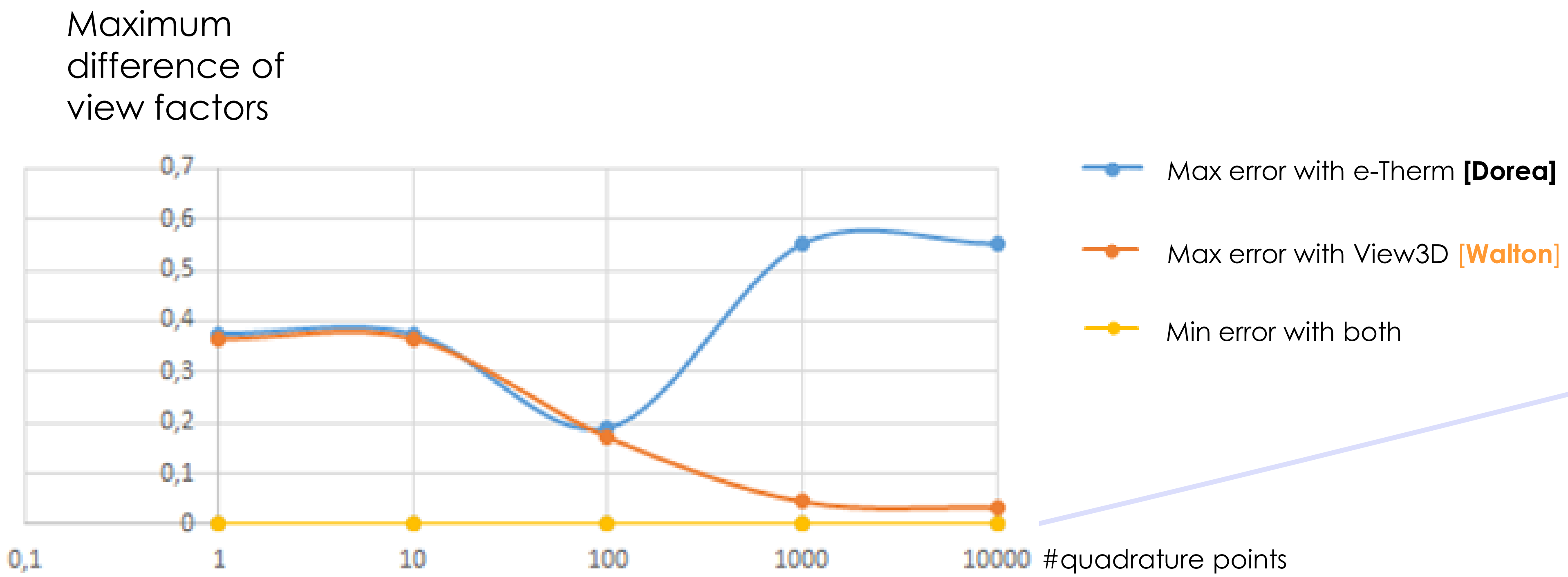
VIEW FACTORS (VF)




Emitter

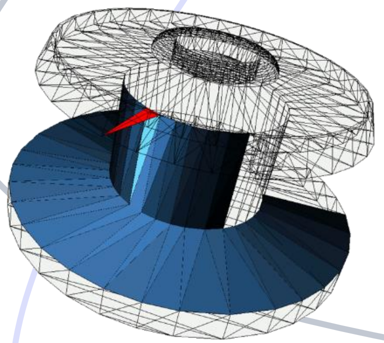
COMPARISONS

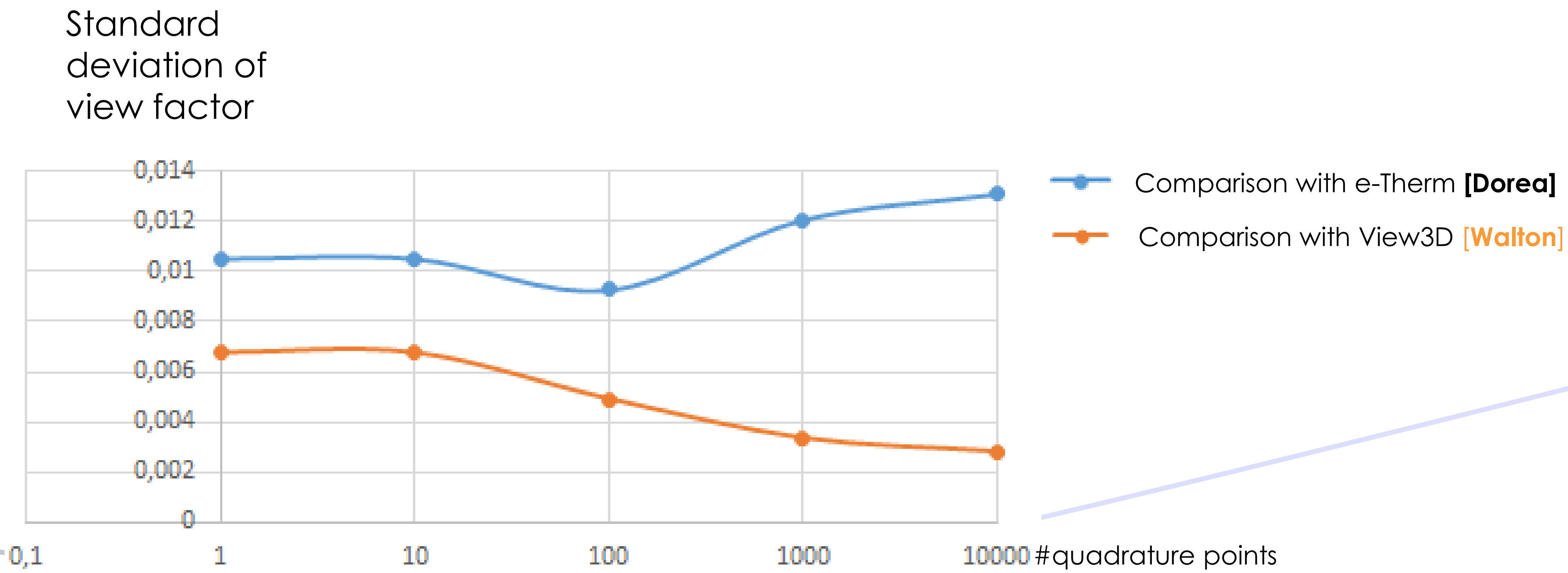




COMPARISONS

DOREA





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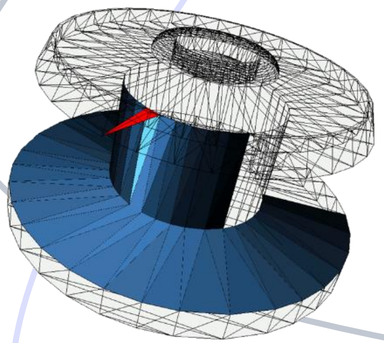
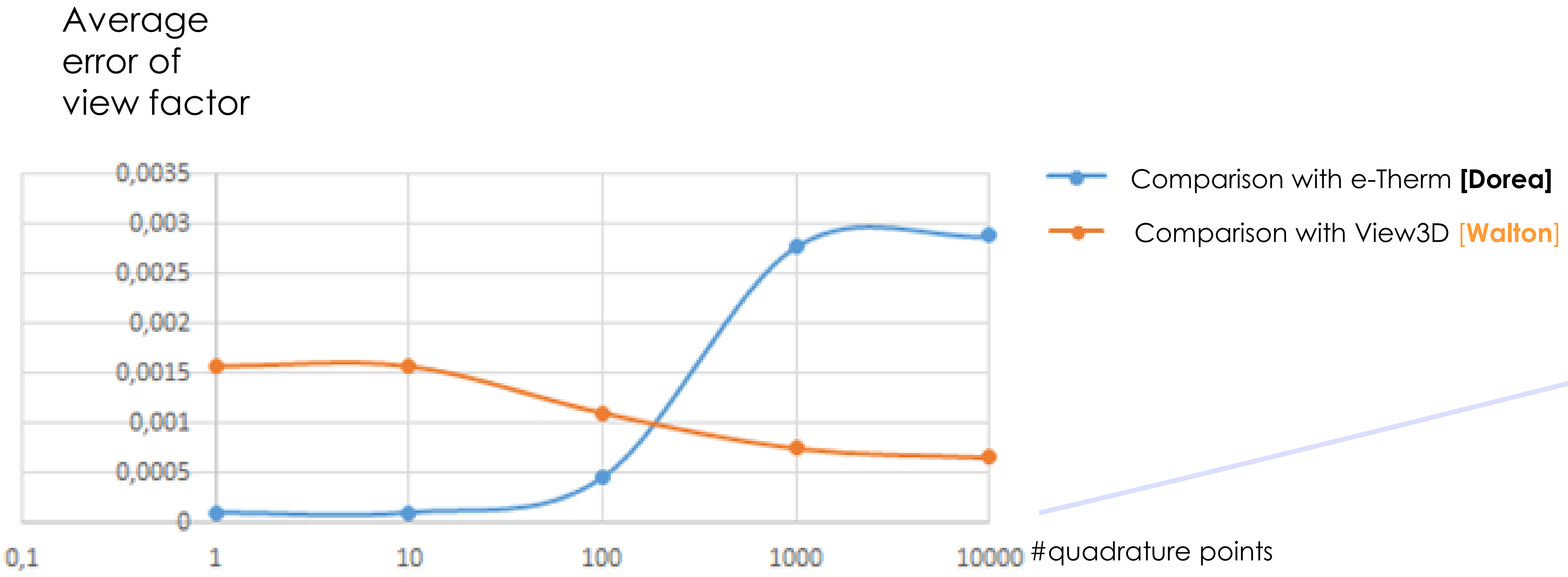
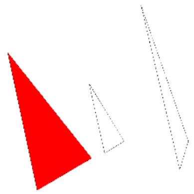


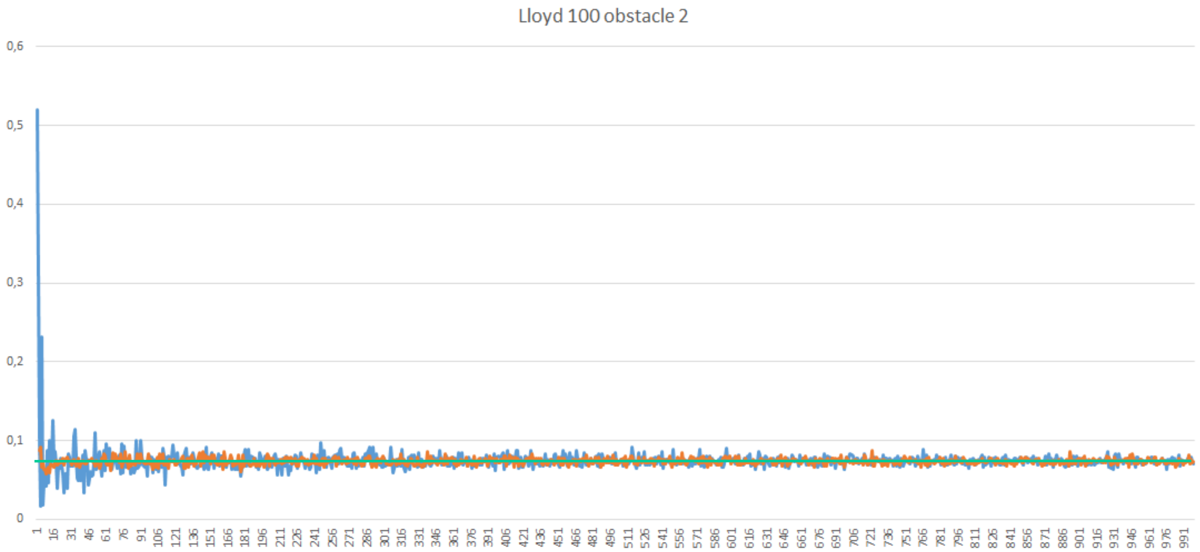


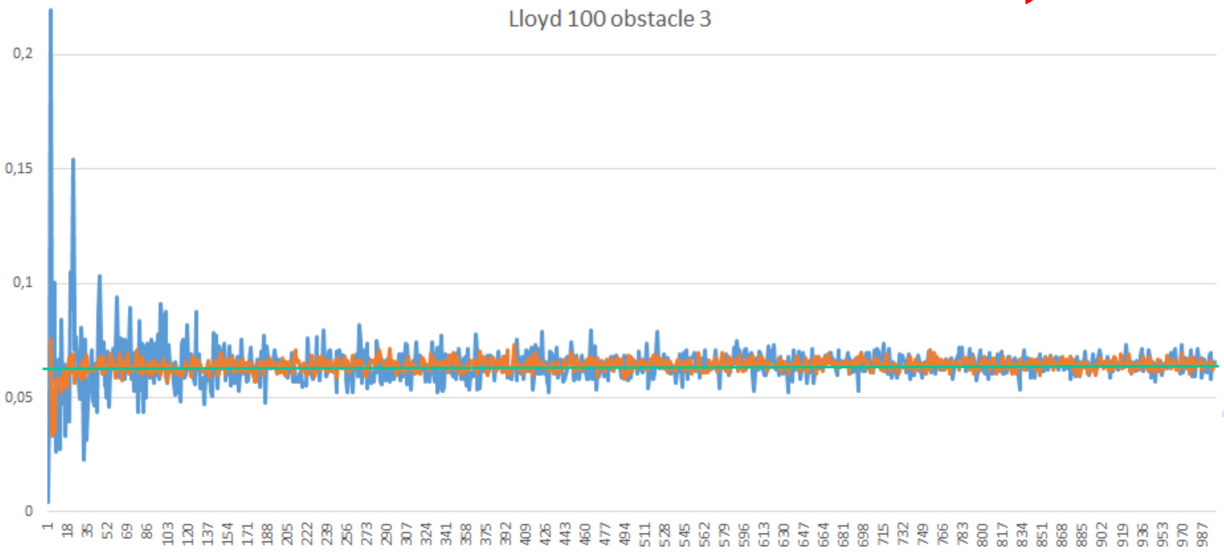
RANDOM SAMPLING VS CVD

Results with two random triangles configuration and an obstacle between them

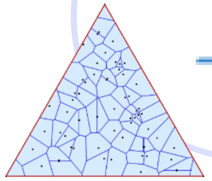


View factor value

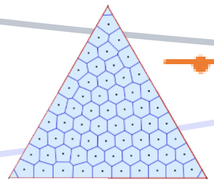




#quadrature points



Random uniform sampling

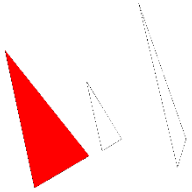


Bounded Centroidal Voronoi

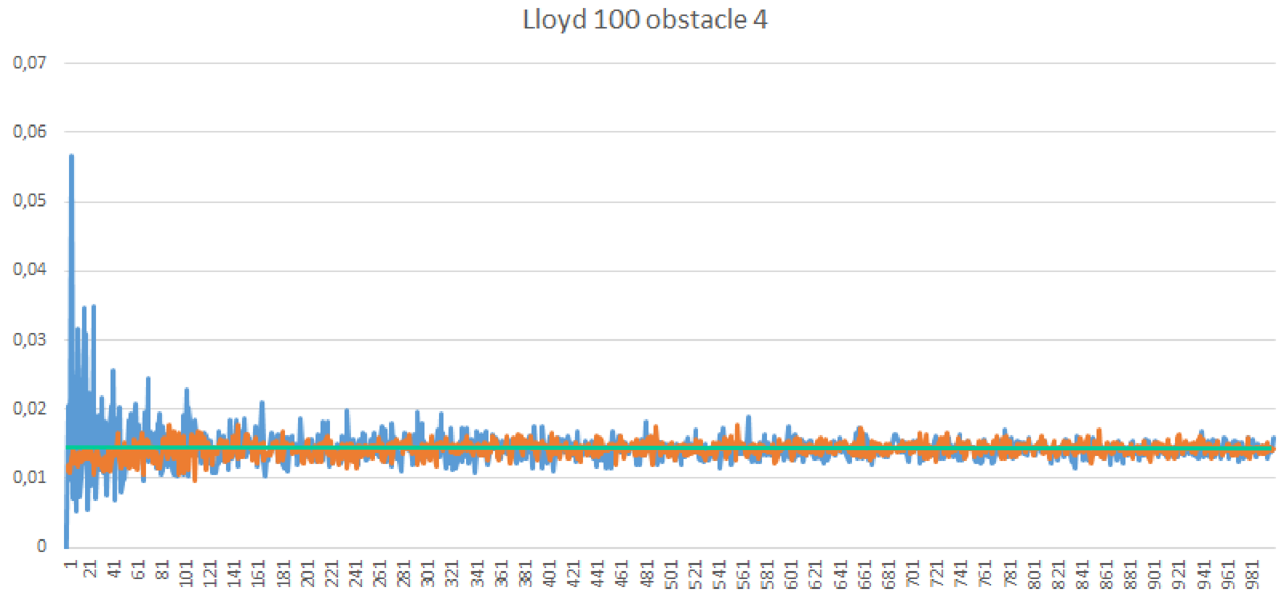
View factor exact value

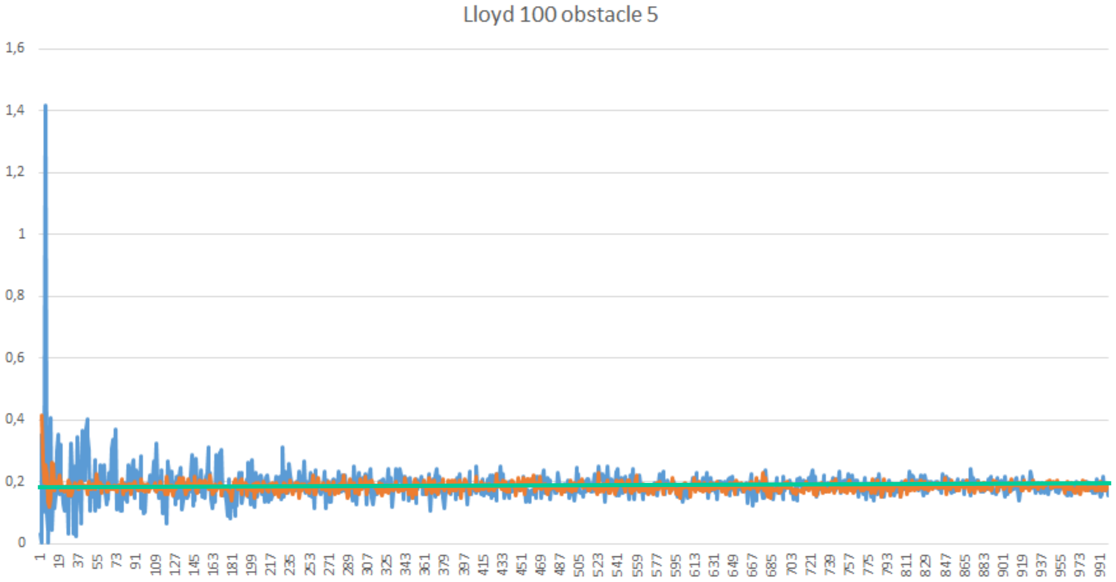
RANDOM SAMPLING VS CVD

Results with two random triangles configuration and an obstacle between them



View factor value





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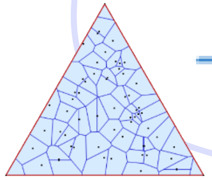
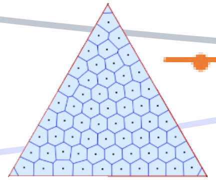


Random uniform sampling

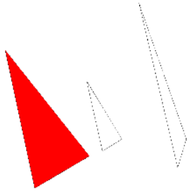


Bounded Centroidal Voronoi

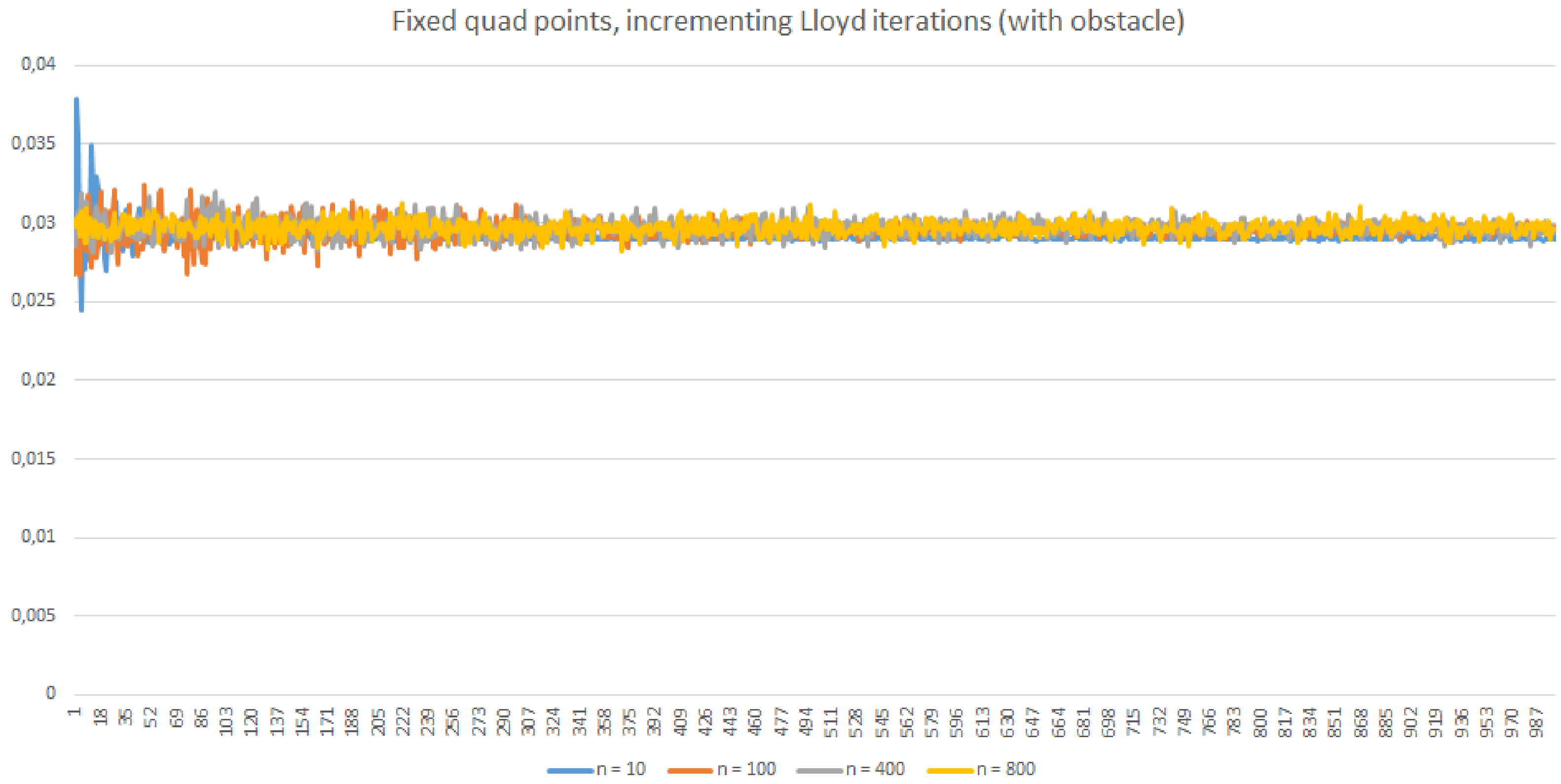
View factor exact value

VARYING #LLOYD ITERATIONS

Results with two random triangles configuration and an obstacle between them



View factor value

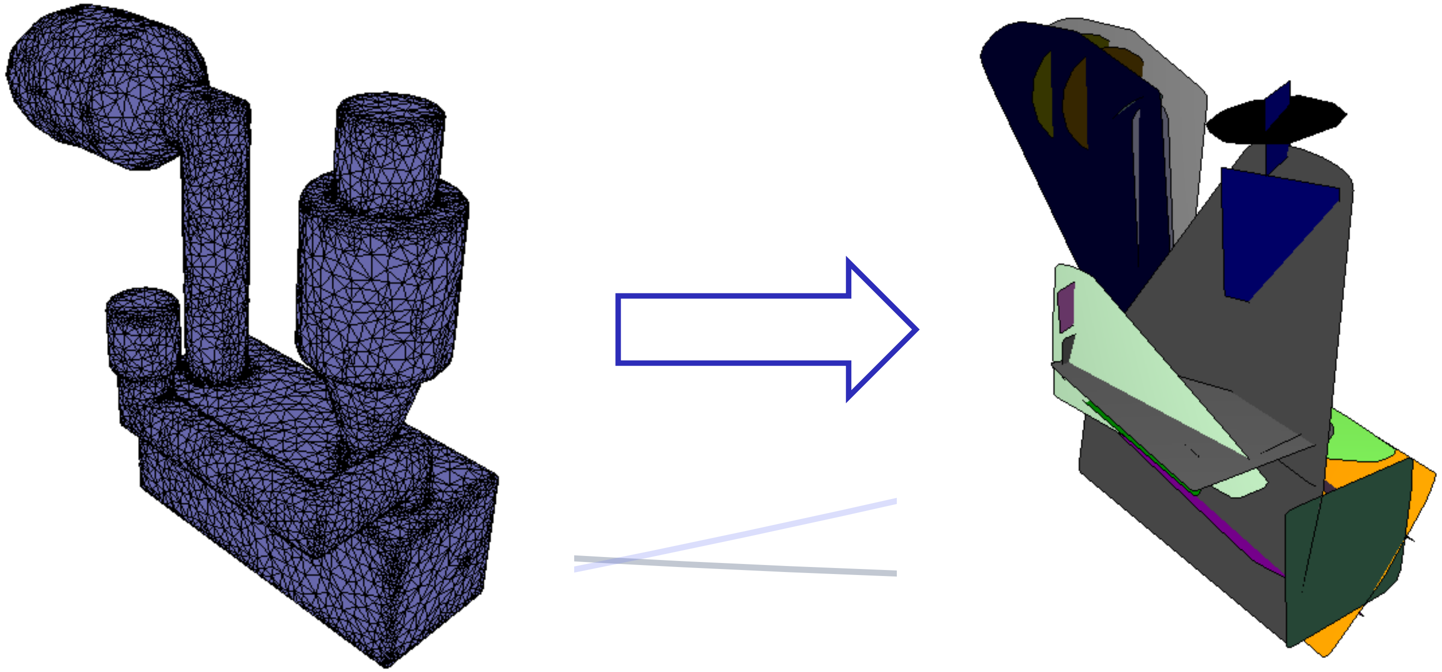


#Lloyd iterations

ON-GOING WORK

	1	2	3	4	5	6	7	8
1	11	12	0	0	0	0	0	0
2	0	22	0	0	0	0	0	0
3	31	32	33	0	0	0	0	0
4	41	42	43	44	0	0	0	0
5	0	0	0	0	55	56	0	0
6	0	0	0	0	0	66	67	0
7	0	0	0	0	0	0	77	78
8	0	0	0	0	0	0	87	88

- **Approximation method guided by preservation of the view factors.** We keep the constraint of the thermal nodes in order to compare the matrices of the radiative surfaces per nodes.



ON-GOING WORK

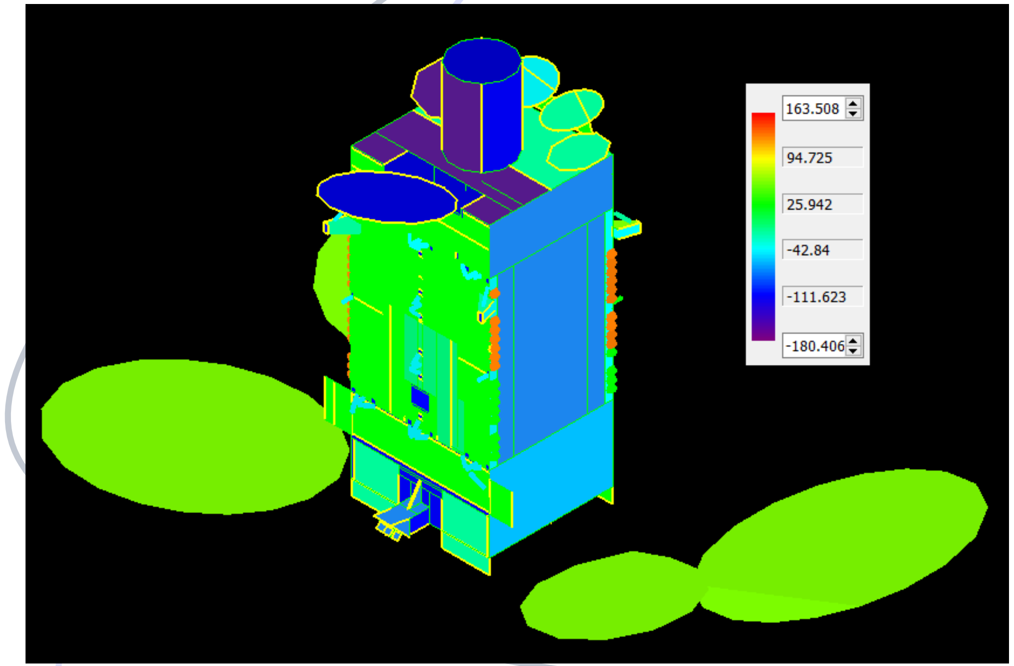


Illustration of the thermal nodes with e-Therm

- **Simplification** via face clustering in order to best approximate the thermal nodes.
- **Comparison with the reference calculation thanks to thermal nodes:**
  - Main idea: compare the radiative surfaces by node matrices from the reference calculation case and the approximation one

WHAT'S NEXT: SUPERVISED MACHINE LEARNING

- **Goal:** learn geometric error metric able to govern an automatic approximation algorithm so that the resulting thermal simulation is as accurate as possible to a reference calculation.
- Constraints = thermal nodes, so we can compare the radiative surfaces of each node before and after approximation.

[**Jacobson**] Thingie10K (training dataset)

THANK YOU

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